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LCA IN TRANSPORTATION

Life cycle assessment of automotive lightweighting through polymers under US boundary conditions

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Abstract
Purpose In the transportation sector, reducing vehicle weight is a cornerstone strategy to improve the fuel economy and energy efficiency of road vehicles. This study investigated the environmental implications of lightweighting two automotive parts (Ford Taurus front end bolster, Chevrolet Trailblazer/GMC Envoy assist step) using glass-fiber reinforced polymers (GFRP) instead of steel alloys.
Methods The cradle-to-grave life cycle assessments (LCAs) for these studies consider a total service life of 150,000 miles for two applications: a 46 % lighter GFRP bolster on the 2010 Ford Taurus that replaced the 2008 steel and GFRP bolster, and a 51 % lighter GFRP running board for the 2007 Chevrolet Trailblazer/GMC Envoy that replaced the previous steel running board including its polymer fasteners. The life cycle stages in these critically reviewed and ISO-compliant LCA studies include the production of upstream materials and energy, product manufacturing, use, and the end-of-life treatment for all materials throughout the life cycle.
Results and discussion The results show that the lighter GFRP products performed better than the steel products for global warming potential and primary energy demand for both case studies. In addition, the GFRP bolster performed better for acidification potential. The savings of fuel combustion and production during the use stage of a vehicle far outweigh the environmental impacts of manufacturing or end-of-life. An even greater benefit would be possible if the total weight reduction in the vehicle would be high enough to allow for the reduction of engine displacement or an elongation of gear ratio while maintaining constant vehicle dynamics. These so-called secondary measures allow the fuel savings per unit of mass to be more than doubled and are able to offset the slightly higher acidification potential of the GFRP running board which occurs when only the mass-induced fuel savings are considered.
Conclusions The lightweight GFRP components are shown to outperform their steel counterparts over the full life cycle mainly due to the reduced fuel consumption of the vehicle in the use phase. To harvest the benefits of light weighting to their full extent, it is recommended that the sum of all mass reductions in the design process be monitored and, whenever feasible, invested into fuel economy by adapting the drive train while maintaining constant vehicle performance rather than leveraging the weight reduction to improve vehicle dynamics.

Keywords Automotive · Design for environment · Fuel economy · Glass-fiber reinforced polymers · Life cycle assessment · Lightweighting

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1 Introduction

The transportation sector today accounts for 70 % of US oil consumption, with personal transportation accounting for about 45 % (EIA 2012). Vehicle fuel economy has become an important part of US policy to reduce domestic oil consumption and reduce air emissions including greenhouse gases, with the Corporate Average Fuel Economy (CAFE) standards for passenger cars and light trucks requiring an estimated combined average mile per gallon level of 35.5 by 2016 and 54.5 by 2025 (EPA/NHTSA 2012). In addition to improving drive train efficiency, aerodynamic and rolling resistance as well as electrical power consumption, vehicle lightweighting is a cornerstone strategy for improving the energy efficiency of road vehicles (ThyssenKrupp 2003; Lovins et al. 2005; SuperLIGHT-CAR 2009; Volkswagen 2011; Alcoa 2012).

While reducing emissions during the use phase may be assumed to improve a vehicle's overall environmental performance, Life Cycle Assessment (LCA) provides a quantitative tool for evaluating the environmental impacts over the complete life cycle, including vehicle manufacturing and end-of-life.

This paper summarizes the results of a study commissioned by the American Chemistry Council's Plastics Division and carried out by PE INTERNATIONAL in 2010 and 2011. The life cycle environmental performance of glass-fiber reinforced polymers (GFRP) in comparison to commonly used steel alloys was assessed in two selected automotive applications: a 46 % lighter GFRP bolster on the 2010 Ford Taurus that replaced the 2008 steel and GFRP assembly, and a 51 % lighter GFRP assist step for the 2007 Chevrolet Trailblazer/GMC Envoy that replaced the 2004 steel assembly that included polymer (TPO) fasteners. The studies have undergone external, independent critical panel review and fully conform to the requirements of the ISO 14040/14044 standards (ACC 2012a, b; ISO 2006a, b).

2 Methods

2.1 System boundary

The system boundary of these cradle-to-grave LCAs includes the production of upstream materials and energy, product manufacturing, use, and the end-of-life treatment for all materials used throughout the life cycle. Design data is based on production at the time of changeover from metal to GFRP parts. The geographic region considered is the North American automotive market.

2.2 Product description and functional unit

In the first case study, a steel assist step assembly (also known as a running board) with polymer (TPO) fasteners designed for the 2007 Chevrolet Trailblazer/GMC Envoy was replaced with a one-piece injection molded, long glass fiber reinforced polypropylene part. Both designs met the GM specification GMW 15951 (Assist Step Loading and Dependability Deflection Test). This specification requires that vertical deflection is no greater than 7.5 mm during static load testing.

The function of the assist step was therefore defined as providing only allowable deflection for a certain load within a certain design footprint over a certain lifetime. Accordingly, the functional unit for this part was set to be providing a stiffness satisfying specification GMW 15951 within an area of 1.761 m by 0.1275 m over a vehicle lifetime of 241.402 km (150,000 mi) assuming an EPA driving cycle of 55 % city and 45 % highway. Note that the area in this functional unit corresponds to the level of quality as defined in Cooper (2003).

The second case study examined the evolution of the 2008 Ford Taurus front end bolster from a steel and GFRP assembly to the 2010 one-piece, direct long fiber thermoplastic (DLFT) polypropylene bolster with glass reinforcement for the hood latch. The services provided by a bolster are manifold. Some of the main requirements are that it has to endure hood slams and hood latch pulls, provide support for the attachment of the radiator, resist fatigue due to vibration, and display certain behaviors in a crash. The functional unit is therefore chosen to be providing structural and component support of a vehicle front over a vehicle lifetime of 241,402 km (150,000 mi) assuming an EPA driving cycle of 55 % city and 45 % highway. The level of quality is passing the Ford latch pull test to support a load of 5,340 N without separation because this was considered the most significant structural requirement.

A service life of 241,402 km (150,000 mi) is selected as an estimate of vehicle design life. Note that this is not intended to represent the actual average lifetime of the vehicle. It rather expresses the author's belief that lightweight measures should break even within a reasonable mileage[1] and is less than the typical lifetime mileage of 244,841 km (152,137 mi) for passenger cars and 289,608 km (179,954 mi) for light trucks (U.S. Department of Transportation 2006).

2.3 Selection of LCIA methodology and types of impacts

The inventory items and impact categories reported were non-renewable primary energy demand, global warming potential, acidification potential, eutrophication potential, and smog potential. Global warming potential and non-renewable primary energy demand were chosen because of their relevance to climate change and energy efficiency, both of which are strongly interlinked, of high public and institutional interest, and deemed to be one of the most pressing environmental issues of our times. Eutrophication, acidification, and smog formation potentials were chosen because they are closely connected to air, soil, and water quality and capture the environmental burden associated with commonly regulated emissions such as NO_x, SO_2, VOCs, and others.

The TRACI impact categorization methodology was used for eutrophication, acidification, and smog (Bare et al. 2003). Because an update of the IPCC factors for climate change was not reflected in the TRACI characterization factors at the time of the study, the authors used the most recent factors as implemented in the CML methodology in its November 2009 release to evaluate global warming potential (IPCC 2007).

2.4 Manufacturing

Collection of primary data on the design of the parts, including the bill of materials, types of processes employed for part

[1] For comparison, note that the average distance from the earth to the moon is 238,855 miles (NASA 2012)

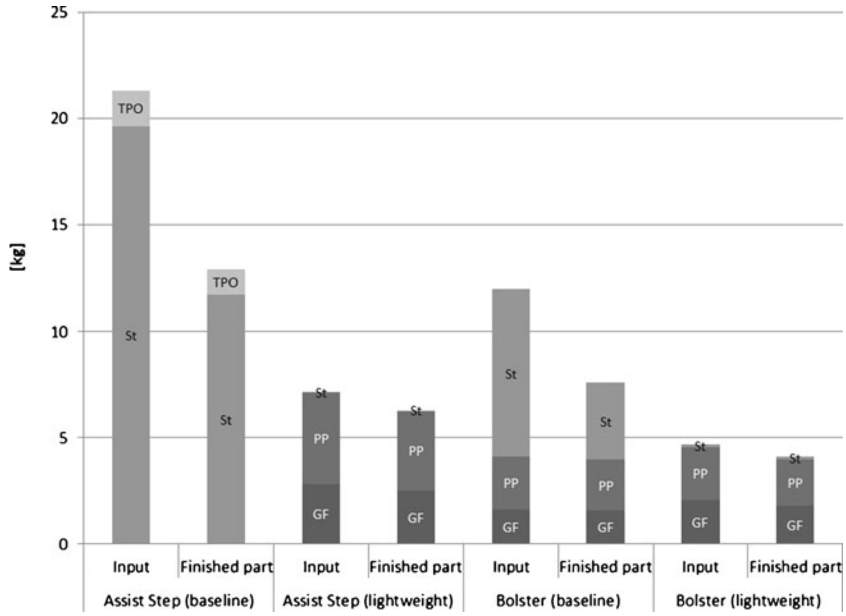

Fig. 1 Material compositions of inputs and finished components

production, and process yields/losses was coordinated by ACC through contacts with the auto and auto part manufacturers. No site-specific manufacturing inventory data (e.g., energy consumption and direct emissions) were collected. Instead, generic inventory data from the GaBi 4 2006 databases were used to represent mechanical processing as well as background processes such as upstream raw materials and energies, transportation, and End-of-Life. For the main materials, US average inventories for the involved polymers as published in the NREL USLCI database were provided by ACC, while global average WorldSteel inventories were used due to the lack of US specific data at the time the study was performed.

The unit processes used to represent part manufacturing were

- compounding (incl. addition of glass fibers) and injection molding for all polymer parts, and
- deep drawing and e-coating for all steel parts,

including all upstream inventories for electricity, lubricants, paint, etc.

The material compositions of the components alongside the input masses into production are shown in Fig. 1. The difference between input and finished part masses are the production scraps, which were consistently sent to recycling and receive a credit ("avoided burden") using worldsteel's global "Value of Scrap" inventory (Atherton 2007; Frischknecht 2010; worldsteel 2011).[2] The only exception was the TPO top cover on the metal assist step, which is used for regrind within the same plant and therefore lowers the internal demand for primary input.

2.5 Transportation

Although no logistics data were collected, transportation of raw materials and final product were modeled assuming a distance of 482.8 km (300 mi) each by truck.

2.6 Use phase savings

For the use phase, fuel savings due to lightweight design over the assumed vehicle lifetime mileage of 241,402 km (150,000 mi) is calculated based on US Environmental Protection Agency (EPA) city and highway driving cycles and the differential efficiency of gasoline engines using the methodology described in Koffler and Rohde-Brandenburger (2010). The method is based on the amount of work necessary to move a certain weight through a certain driving cycle and the differential efficiency of the internal combustion engine.

In order to do so, first the mass induced energy demand needs to be calculated using the following formula:

$$W_{sum} = m * ((1-d) * g * f_R * C_{WR} + C_{Wa}) \qquad (1)$$

with

W_{sum}	energy demand [MJ]
m	mass [kg]
d	share of deceleration phases in driving cycle [%]
g	gravitational constant [m/s^2]
f_R	rolling resistance coefficient (dimensionless)
C_{WR}	constant for rolling resistance [m]; specific to driving cycle
C_{Wa}	constant for acceleration resistance [m^2/s^2]; specific to driving cycle

[2] The Value-of-Scrap is the difference of a hypothetical 100 % primary BOF (without any scrap inputs) and a 100 % secondary EAF and accounts for the EAF recycling efficiency. Note that all scrap inputs into manufacturing are also assigned a burden using the same worldsteel inventory to avoid double-counting.

The mass induced energy demand W_{sum} for moving 100 kg of weight through the US combined fuel economy driving cycle over a distance of 100 km therefore is $W_{sum}(100\ kg, 100\ km) = (100\ km/17.2\ km) * m * ((1-\ d) * g * f_R * C_{WR} + C_{Wa}) = 5.81 * 100\ kg * (0.83 * 9.81\ m/s^2 * 0.01 * 17,198\ m + 2,221\ m^2/s^2) = \tilde{}2.1\ MJ$ as 17.2 km is the combined distance of the EPA city and highway driving cycle and 17 % is the combined deceleration phases of both..[3] [4]

Assuming 5 % losses in the automatic gearbox, the mass-induced fuel consumption V of naturally aspirated gasoline engines for moving 100 kg through the EPA combined driving cycle over a distance of 100 km using a differential engine efficiency of 0.073 liters of gasoline per MJ of output (Koffler and Rohde-Brandenburger 2010) calculates to:

$$\begin{aligned} V_{100\ kg} &= 2.1\ MJ/(100\ km * 100\ kg) * 1.05 * 0.073\ l/MJ \\ &= 0.161\ l/(100\ km * 100\ kg) \\ &= 0.031\ gal/(100\ mi * 100\ lb) \end{aligned}$$

Note that the above calculations assume that no constructive changes are made to the vehicle itself. They correspond to the amount of mass-induced fuel consumption in a given driving cycle, and vice versa to the reduction in fuel consumption when that weight is removed from the vehicle (e.g., empty trunk vs. full trunk). Yet, this latter Fuel Reduction Value (FRV), i.e., the fuel savings in comparison to a given reference, can be significantly increased when one considers unchanged vehicle dynamics as an objective to preserve functional equivalence on the vehicle level before and after any lightweighting measures.

In theory, each mass reduction improves the vehicle's acceleration and dynamic performance. An adaptation of the drive train (i.e., the reduction of engine capacity or the elongation of the gear ratio) may vice versa further increase the fuel economy while preserving the vehicle dynamics. A multitude of simulations of drive train adaptations rendered fuel reduction values that are a factor 1.9 to 3.0 higher than the values without additional drive train adaptations, with an average of 2.37 (Koffler and Rohde-Brandenburger 2010).

It was therefore assumed that the ratio between no drive train adaptation and adapted drive train is the same for the US combined driving cycle as for the New European Driving Cycle (NEDC). The potential decrease in fuel consumption with adaptation V^* for naturally aspirated gasoline engines then amounts to roughly:

$$\begin{aligned} V^*_{100\,kg} &= 0.16\,\mathrm{l}/(100\,km * 100\,kg) * 2.37 \\ &= 0.38\ \mathrm{l}/(100\,km * 100\,kg) \\ &= \tilde{}0.07\ gal/(100\ mi * 100\ lb) \end{aligned}$$

Carbon dioxide emissions from fuel combustion were then calculated using the average EPA emission factor of 2.32 kg/l (19.4 lb/gal) of gasoline. Sulfur dioxide emissions were calculated based on the fuel's sulfur content (30 ppm). Due to the fact that there is not sufficient evidence that

a) the sum of all lightweight design measures in the car (which are unknown) actually allowed for a drive train adaptation, and
b) that the involved car manufacturers actually preferred fuel economy over performance within the design process,

The adapted fuel reduction value was only considered in a what-if scenario in this study.

Because the above calculations use a lot of assumptions, the following data points were tested in a subsequent uncertainty analysis: share of deceleration phases which are strong enough to allow the engine to enter throttle cut-off mode (17 %), rolling resistance coefficient (0.01), automatic gearbox loss (5 %), and the ratio of savings with an adapted drive train to no adaptation (2.37).

2.7 End-of-life

It was assumed that 98 % of the steel material is recovered for recycling at end-of-life. The recycled steel is awarded a recycling credit ("avoided burden") represented by worldsteel's global "Value of Scrap" inventory (Atherton 2007; Frischknecht 2010; worldsteel 2011). After discussion with manufacturers, it was further assumed that all polymer material is landfilled and that it does not decompose into CO_2 and/or CH_4 in the landfill.

2.8 Secondary mass changes

In some cases, lightweighting automotive components or assemblies can lead to secondary mass changes in another component or in a number of components in a kind of "snowball effect." A classic example is the downsizing of the brakes, chassis parts, drive train, fuel tank, and neighboring components due to a major decrease in the vehicle's body-in-white weight.

In many other cases, however, secondary mass changes are not as easily allocated to an initial weight reduction in a single component or assembly. In the case that a multitude of independent, moderate weight reductions *in sum* enable a secondary mass change, this mass change would need to be allocated accordingly between the individual measures to avoid double-counting. This is extremely challenging in practice unless one has full knowledge of all weight reduction

[3] (55 %×11.04 miles+45 %×10.26 miles)

[4] (55 %×25 %+45 %×8 %)

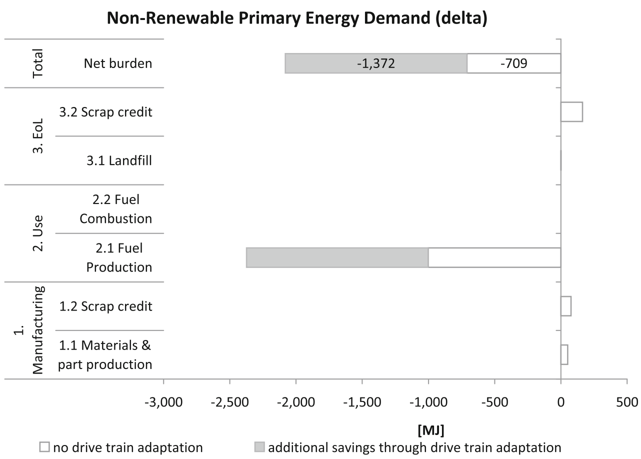

Fig. 2 PED results—assist step

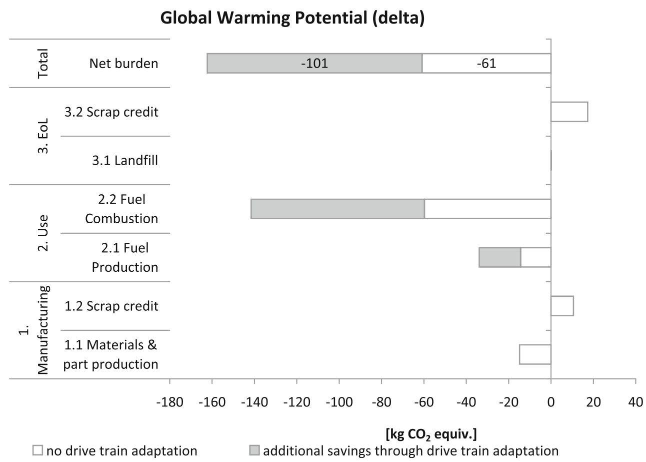

Fig. 3 GWP results—assist step

measures in the entire vehicle and knows in which chronological order they occurred to properly demonstrate the cause-and-effect chain.

Also, secondary mass changes may not always occur in reality even though they are theoretically possible. First, redesigning an existing component is an additional cost that may not be warranted by the achievable benefit. Second, downsizing components like engines, transmissions, brakes, etc. is not a continuous exercise where any percentage weight reduction can be directly transformed into secondary mass changes, but rather a step function whose characteristics depend on the specific components available to the OEMs from their product portfolio or suppliers.

The case studies at hand therefore did not consider any mass changes beyond the described components since there was no proof or indication of any mass changes that resulted immediately from the weight changes under study.

3 Results

As a normalized comparison showed that the differences between the steel and GFRP parts regarding eutrophication and summer smog potential were only marginal and did not provide any new or deviating insights,[5] Figs. 2, 3, 4, 5, 6, and 7 focus on the results for non-renewable primary energy demand, global warming potential, and acidification potential. Note that the values are calculated as the lightweight results minus the baseline results. A result carrying a negative sign therefore means that the lightweight product outperformed the baseline product (net reduction).

Results are presented as deltas due to the fact that the use phase emissions can only be calculated as a difference from the baseline if secondary measures are subsequently to be accounted for because these additional measures do not apply to the baseline components. Using the GFRP product therefore results in less fuel consumption and combustion emissions compared to the baseline, while the baseline itself does not entail any "fuel reduction." It is hence represented by the vertical axes in Figs. 2, 3, 4, 5, 6, and 7.

As can be seen, the GFRP parts show net reductions of life cycle burdens, with the only exception of the acidification potential for the assist step when no drive train adaptations are assumed (Fig. 4). In that case, the substantial reduction of acidifying emissions during fuel production is offset by the higher burden of the manufacturing stage and further aggravated by the lack of an EoL recycling credit due to landfilling of the GFRP part. This results in a net burden when subtracting the baseline scenario values.

Yet, when adding the additional savings made possible by an adaptation of the drive train (reduction of engine replacement or elongation of gear ratio), this net burden is again overcompensated and the lightweight components achieve net reductions in all impact categories.[6]

4 Discussion

It is obvious that the outcomes of any kind of lightweighting LCA ultimately depend on two questions:

1. How high will the fuel savings caused by the weight reduction actually be?
2. How likely is it that the total weight reduction in the vehicle (which may be caused by other lightweighting measures as well) will allow for an adaptation of the drive train without compromising vehicle dynamics?

As to the prior question, the calculation of the resulting fuel reduction was based on a variety of uncertain parameters in

[5] Please refer to http://plastics.americanchemistry.com/Education-Resources/Publications/ for details.

[6] This applies likewise to eutrophication potential and smog formation potential (not shown).

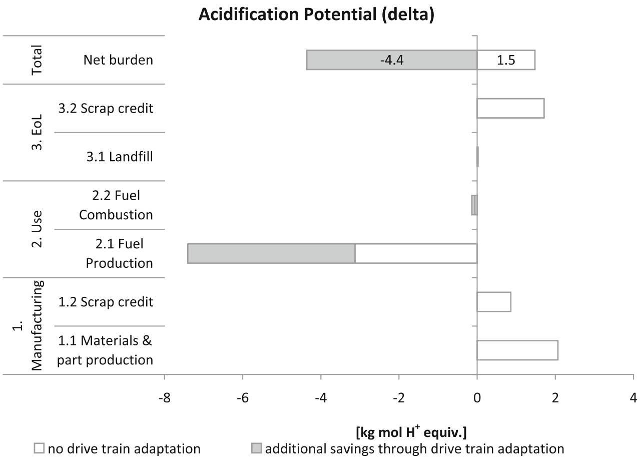

Fig. 4 AP results—assist step

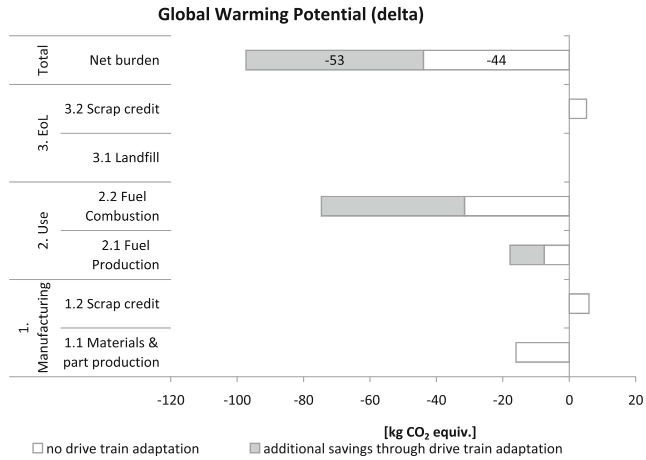

Fig. 6 GWP results—bolster

this study as described in section 2. Due diligence therefore demands that the influence of these assumptions on the results are tested in an uncertainty analysis.

Table 1 shows the parameters that were included in a Monte Carlo simulation as well as their respective upper, lower, and base case (Transportation Research Group 2006; Schlegel et al. 2009). The upper and lower limits were then used to establish uniformly distributed uncertainty intervals for each parameter, from which random values were drawn 10,000 times and combined to 10,000 individual values for the fuel reduction value $FRV_{100\ kg,\ 100\ km}$. This procedure was applied to a scenario without as well as to a scenario with drive train adaptation.

Table 2 shows the results of the Monte Carlo simulation. Two things can be concluded from these values: first, that the base case appears to be a conservative assumption of the expected reduction in fuel consumption as the mean FRV value across all 10,000 runs is about 9 % higher than the 0.161 l/(100 km × 100 kg) or 0.031 gal/(100 mi × 100 lb) calculated in section 3, and second, that this value nevertheless appears to be a robust estimate as the distance to the ascertained mean is only about one standard deviation (no drive train adaptation) or less than half a standard deviation (with drive train adaptation). In addition, it can be stated that the calculation of the FRV itself is a fairly robust exercise as the maximum standard deviation of ~20 % is on a reasonable level.

As to the second question, it was not possible to ascertain within this study whether the described lightweighting measures contributed to the total vehicle weight reduction to an extent that actually allowed for a drive train adaptation. Such an evaluation cannot be performed by third parties who are not involved in the vehicle design process until the final design freeze. Due to the lack of more detailed information, the two scenarios are presented as equally likely.

5 Conclusions

The study showed that lightweighting the selected automotive components by replacing steel with GFRP parts leads to an

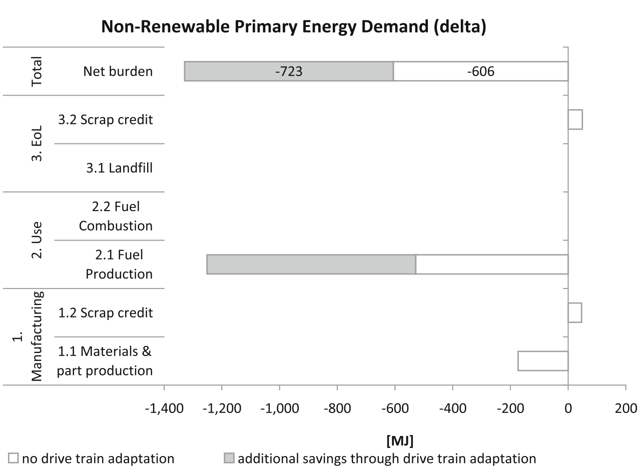

Fig. 5 PED results—bolster

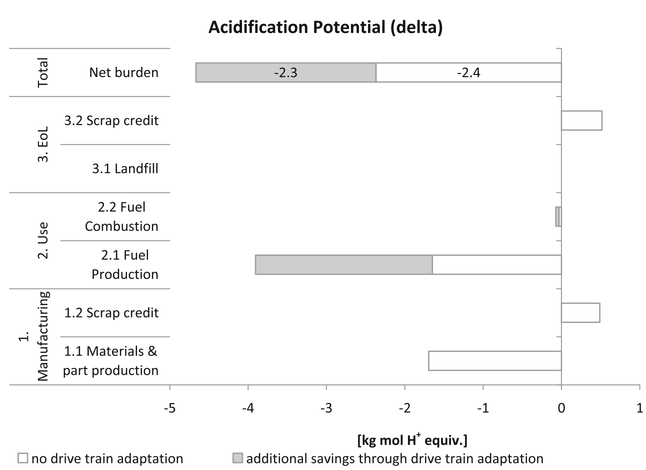

Fig. 7 AP results—bolster

Table 1 Use phase parameters for Monte Carlo simulation (10,000 runs, uniform distribution)

	Lower limit	Base scenario	Upper limit
Deceleration in city driving cycle (throttle cut-off) [%]	0^b	25	25^w
Deceleration in highway driving cycle (throttle cut-off) [%]	0^b	8	8^w
Rolling resistance coefficient f_R	0.007^w	0.01	0.014^b
Automatic gearbox losses [%]	5^w	5	10^b
Ratio of fuel savings with adaptation to no adaptation	1.66^w	2.37	3.08^b

b best-case assumptions, *w* worst-case assumption

Table 2 Monte Carlo simulation results (10,000 runs, uniform distribution)

	No adaptation		With adaptation	
	Mean relative to base	Standard deviation	Mean relative to base	Standard deviation
Bolster	109 %	9 %	109 %	20 %
Assist step	109 %	8 %	109 %	19 %

overall improved environmental profile if it is assumed that the total weight reduction in the vehicle allows for a drive train adaptation (reduction of engine displacement or elongation of gear ratio) while preserving vehicle performance. In fact, lightweighting the running board on all 148,658 2007 GMC Trailblazers would then reduce the emission of greenhouse gases by the equivalent of combusting more than 10.2 million liters (2.7 million gallons) of gasoline over the life of the vehicles, and lightweighting the bolster on all 70,666 2010 Ford Taurus models would reduce the emission of greenhouse gases by the equivalent of combusting over 2.9 million liters (770,000 gallons) of gasoline over the life of the vehicles.[7]

If such an adaptation does not take place, these net reductions are significantly reduced and can even turn into a net increase in life cycle burden as demonstrated in the case of the acidification potential of the assist step.

To harvest the benefits of light weighting to their full extent, it is therefore recommended that the sum of all mass reductions in the design process be monitored and, whenever feasible, invested into fuel economy by adapting the drive train while maintaining constant vehicle performance rather than leveraging the weight reduction to improve vehicle dynamics.

While this scenario will become increasingly likely in the future with stricter CAFE standards, it is not common knowledge among LCA practitioners and audiences today that a drive train adaptation is crucial to maximize the benefits of automotive light weighting in application.

[7] Based on total CO_{2e} savings converted to gallons of gasoline using a C content of 0.855 kg C/kg and a density of 0.735 kg/l.

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